

The Production of Fissile Materials for Nuclear Weapons and Nuclear Power



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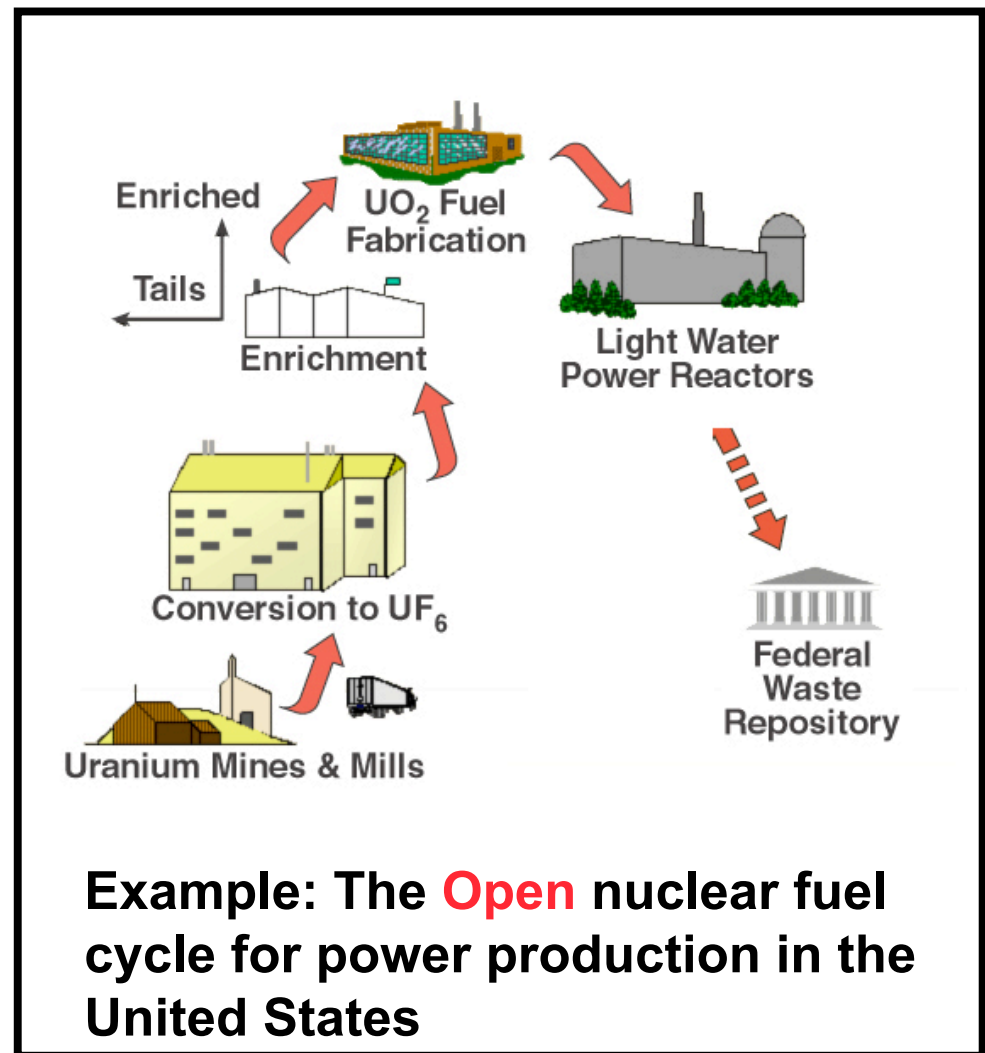
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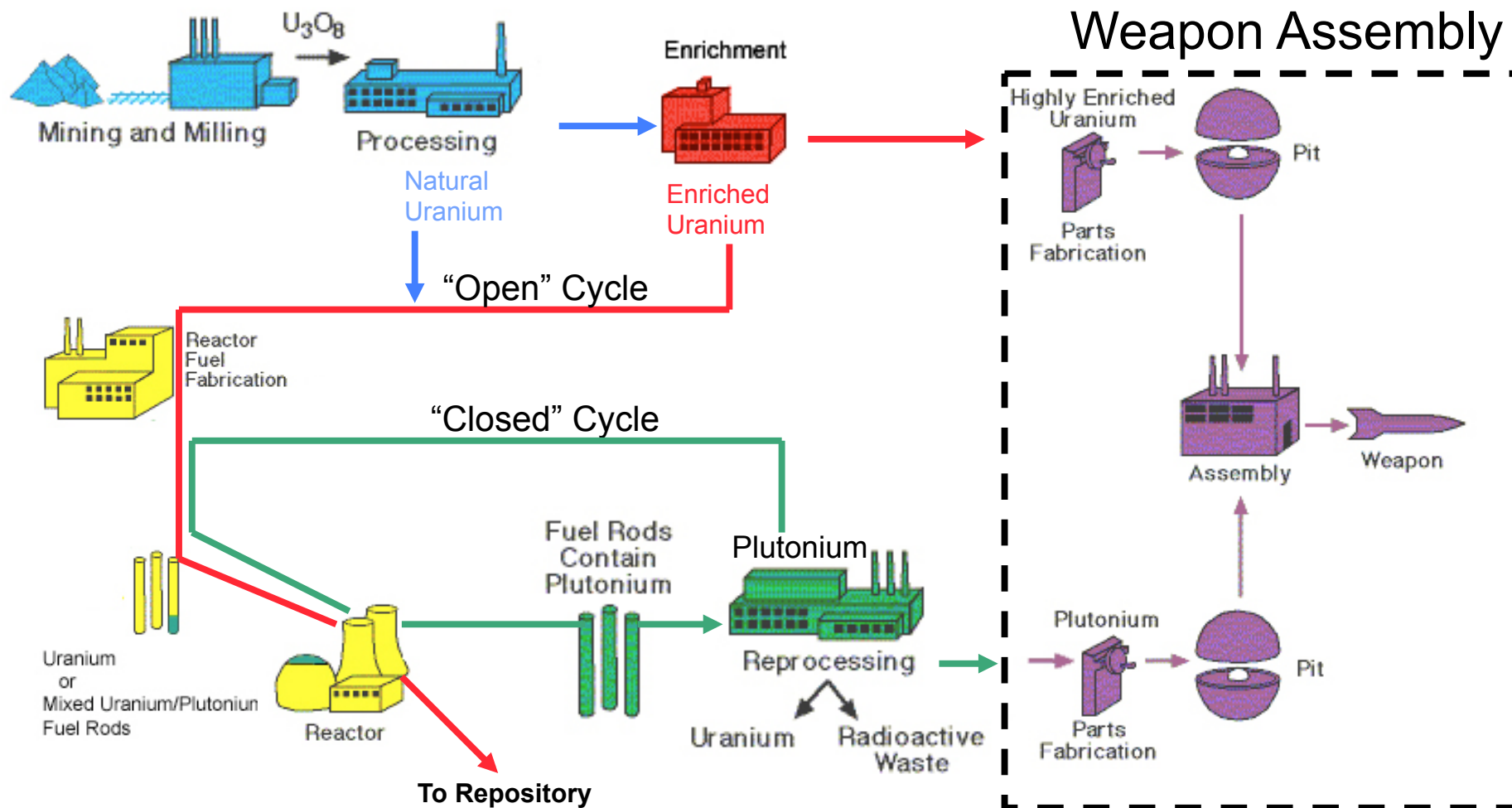
Definition of the Nuclear Fuel Cycle

- The set of processes to obtain, refine, and exploit nuclear material for a specific purpose
 - There are several different types and subcategories
 - power
 - weapons
 - naval reactor fuel
 - radioisotope production
 - research
 - Cycles also vary:
 - in degree of opportunity to obtain directly weapons-usable material
 - In degree of difficulty in safeguarding
- * New cycle are now being contemplated in the US and world-wide – their proliferation consequences must be carefully considered





Civil and military fuel cycles overlap



This recognition is the basis for the nuclear nonproliferation treaty

Why is there overlap? because enormous amounts of energy can be extracted from small amounts of fissile material – slowly or quickly



Fission of uranium and plutonium can release many orders of magnitude more energy per unit of mass than 'chemical' combustion of sources like coal



The energy density of Coal:
about 10^7 Joules/Kg

Three tons (3000 kg) of
fissile material in the ~10
cubic meter

San Onofre Unit 2 reactor
core power a few million
homes in O.C. for a year

**Fissile material produces 10,000,000
times energy per unit mass than coal**



The energy density of Plutonium:
about 10^{14} Joules/Kg

Some isotopes of plutonium and uranium also make great explosives, requiring little mass per unit of destructive power

IAEA Standard: **8 kg** of Plutonium or **25 kg** of High Enriched Uranium suffice to make a Hiroshima size (or greater yield) nuclear weapon



What is fissile material ?

- **Material that can be made to undergo a nuclear chain reaction, consisting of successive fissions, with high energy release**
 - Controlled release = Reactor
 - Uncontrolled release = Explosive
 - Also called “Special Nuclear Material”, “Special Fissionable Material”
- **For practical purposes, there are two materials for weapons production**
 - Highly Enriched Uranium and Plutonium
- **And three ways to acquire them**
 - Highly Enriched Uranium may be obtained via Enrichment
 - Plutonium may be obtained via Reprocessing
 - Either may be obtained via theft or purchase
- **Other possibilities for weapons manufacture exist**
 - ^{233}U ; neptunium; americium
 - There are far less of these materials in the world



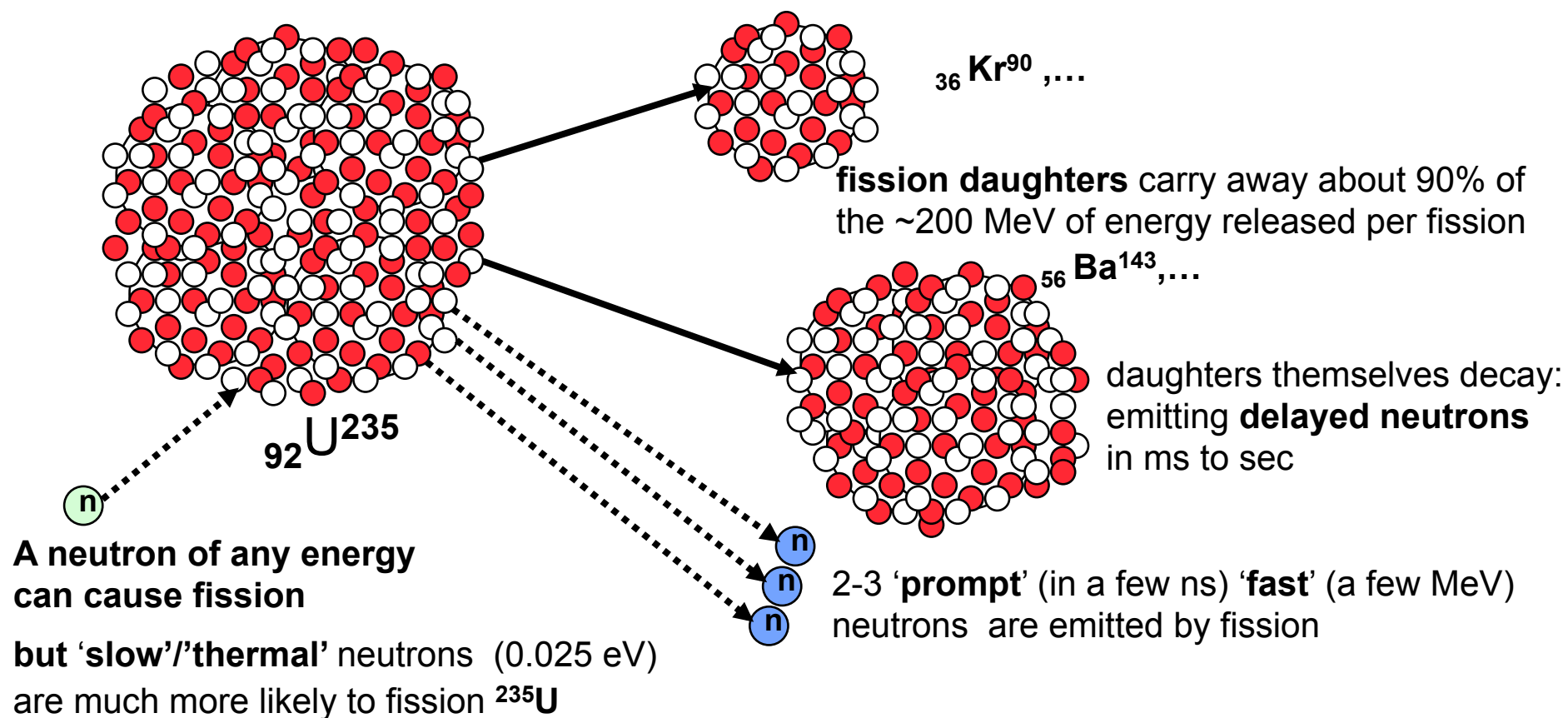
Acquiring fissile material is the most difficult step in making a nuclear weapon

- Dominates the time to achieve a nuclear weapons capability
- Dominates the cost of a nuclear weapons program
- **Enrichment** (Isotope separation) of uranium and **Reprocessing** for plutonium separation from spent fuel are particularly difficult
- Also difficult:
 - **making gaseous uranium to feed enrichment**
 - **producing heavy water or highly pure graphite for reactors that use these moderating materials**
 - **building a nuclear reactor**

These technical obstacles can drive would-be proliferators, especially subnational groups, towards theft, collusion, bribery and other non-technical approaches, to obtain materials and/or technologies

Nuclear Fission:

one neutrons in, a few neutrons out, plus energy



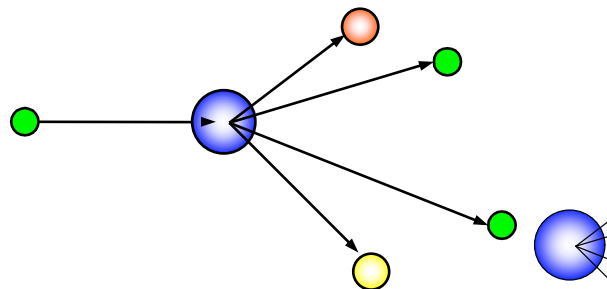
This 'fissile' property of ^{235}U (and ^{239}Pu) is what allows the chain reactions that enable both bombs and reactors

not shown: 8-10 **gamma-rays** (~1 MeV each) also emitted by fission – very useful for detection but don't affect chain reactions in bombs and reactors



With enough fissile mass and density, controlled or runaway nuclear chain reactions can occur

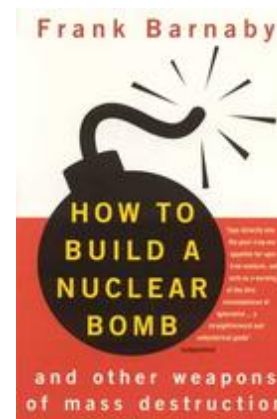
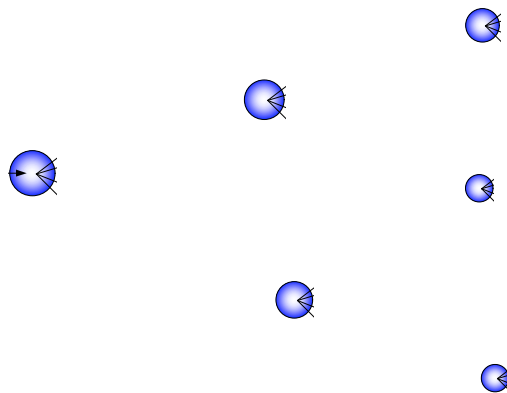
*A system that sustains a **controlled chain reaction** is called “critical”*



Reactor cores
are critical –

Delayed neutrons
control criticality in reactors

*A system that sustains a **runaway chain reaction** (for several hundred billionths of a second) is called “supercritical”*



Bombs are
supercritical

System is
supercritical
until it blows
itself apart

Vocabulary interlude - fissile versus fissionable versus fertile



- **Fissile materials** – can be fissioned by neutrons of any energy, including zero kinetic energy, capable of sustaining a chain reaction

^{235}U , ^{239}Pu , ^{241}Pu



The Ford Pinto

- **Fissionable materials** – can be fissioned only by neutrons above an ~ 1-2 MeV threshold – cannot alone sustain a chain reaction

^{238}U , ^{232}Th



The Ford Volvo

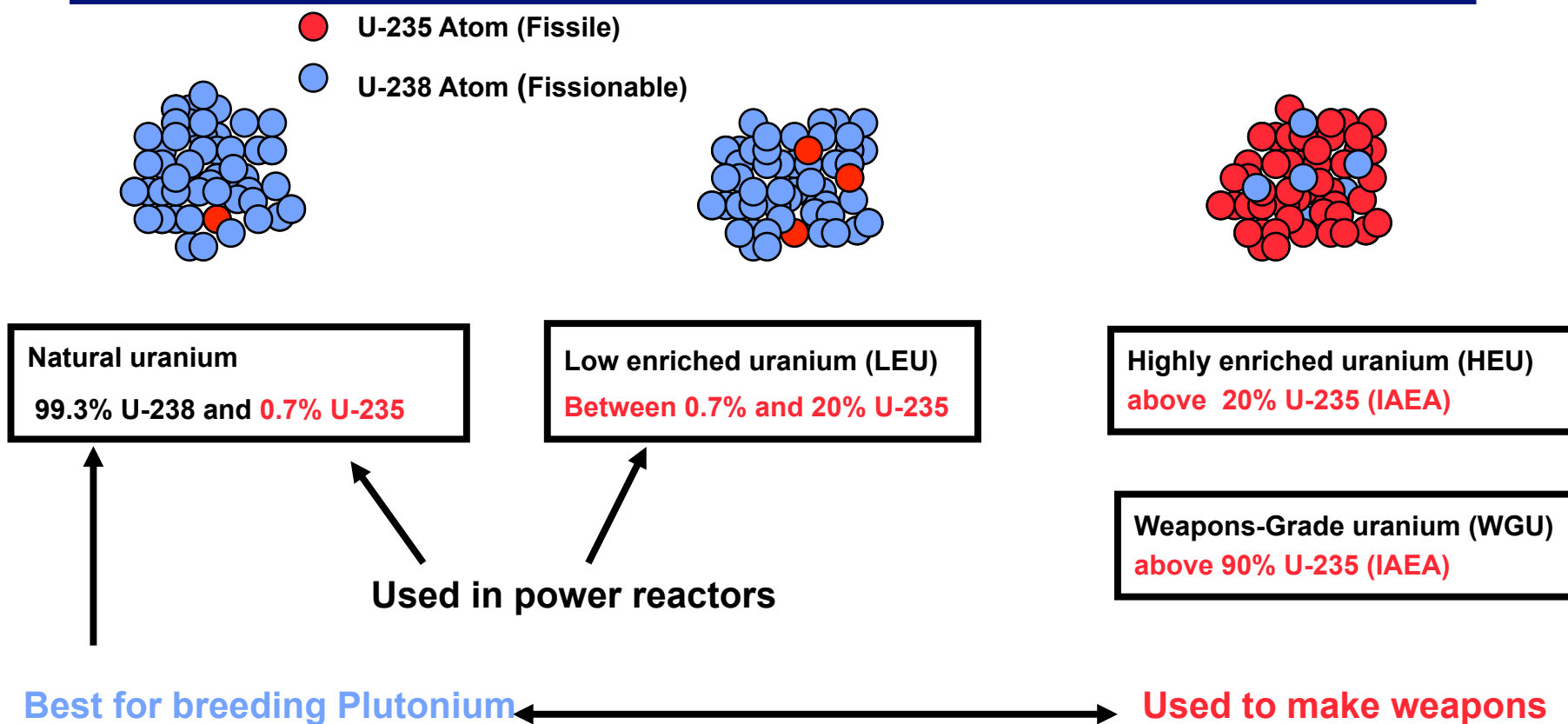
- **Fertile materials** – capable of *absorbing* neutrons to create or 'breed' fissile material

(more about this in a few moments..)

^{238}U , ^{232}Th

?

Uranium provides fuel for power reactors, can be used to make a nuclear weapon, and is the source of all plutonium

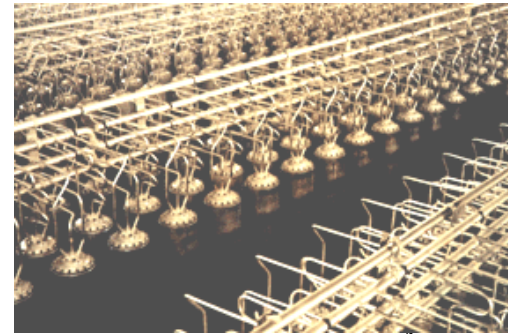


- Uranium enrichment is one of two main paths to a nuclear weapon
- Fortunately, it is fairly difficult - chemically identical atoms of slightly different mass have to be separated

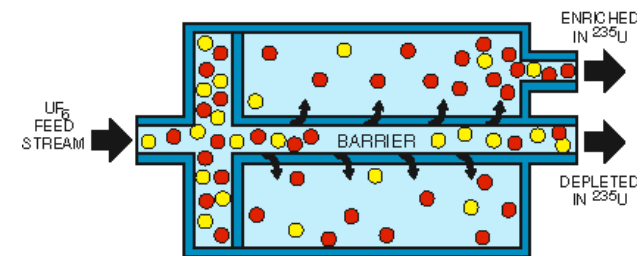


Four methods of uranium enrichment have been used on a large scale

- **Gas Centrifuge: spin uranium hexafluoride gas**
 - High capital cost
 - Low energy consumption
 - UK, Netherlands, Germany, Russia, China, Japan, Pakistan, Iraq, Brazil, Iran, Libya
- **Gaseous Diffusion: force UF₆ gas through a membrane**
 - Lower capital cost
 - High energy consumption
 - US, Russia, France
 - Large size
- **Electromagnetic Isotope Separation (EMIS): accelerate uranium atoms in a magnetic field**
 - Very high energy consumption
 - Early US, Iraq
- **Aerodynamic/Jet Nozzle: stationary wall centrifuge**
 - High capital cost
 - High energy consumption
 - South Africa



Gas Centrifuge Cascade



Gaseous Diffusion Unit

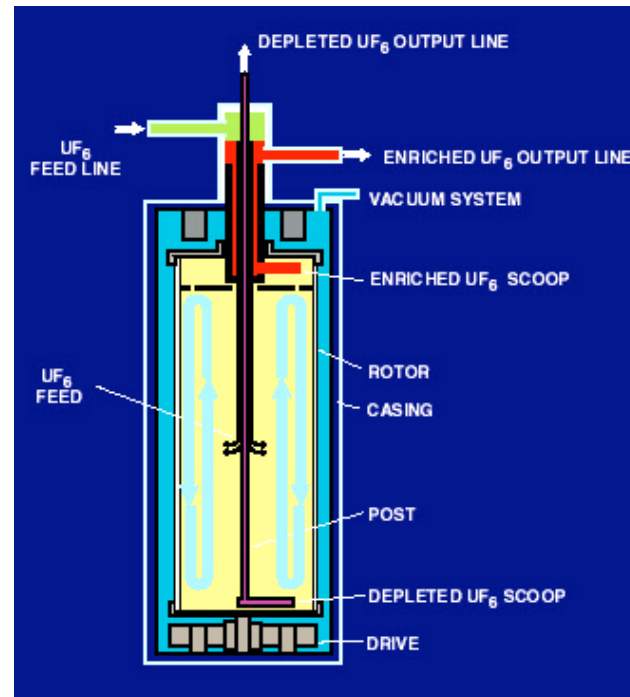


Calutron Track

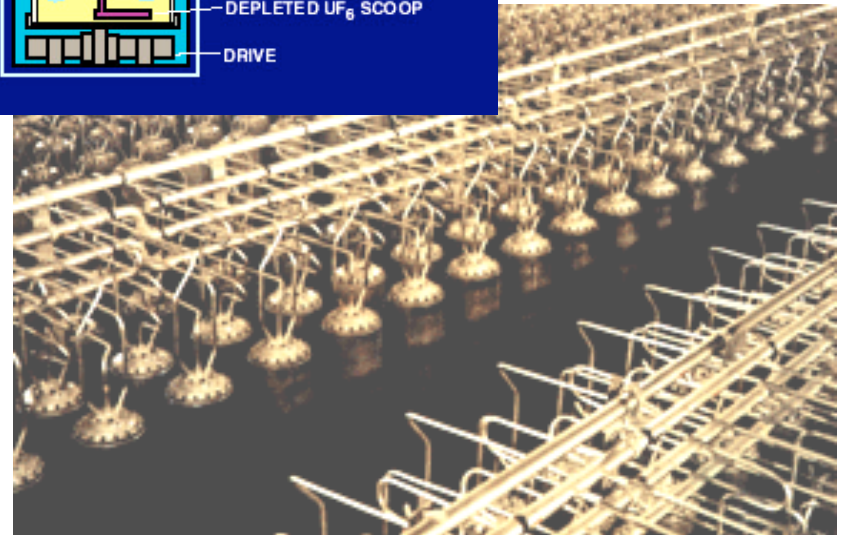


Gas centrifuge technology is particularly sensitive

- Gas centrifuge plants to produce HEU for weapons have **no unique signatures**
 - Modest size
 - Low energy consumption
- Gas centrifuge plants can be **easily reconfigured to adjust the enrichment level**
- Gas centrifuge technology has **spread all over the world**
 - A.Q. Khan the most visible distributor
- Many countries have the **capability to produce gas centrifuge equipment**
 - Key components and manufacturing equipment are export controlled



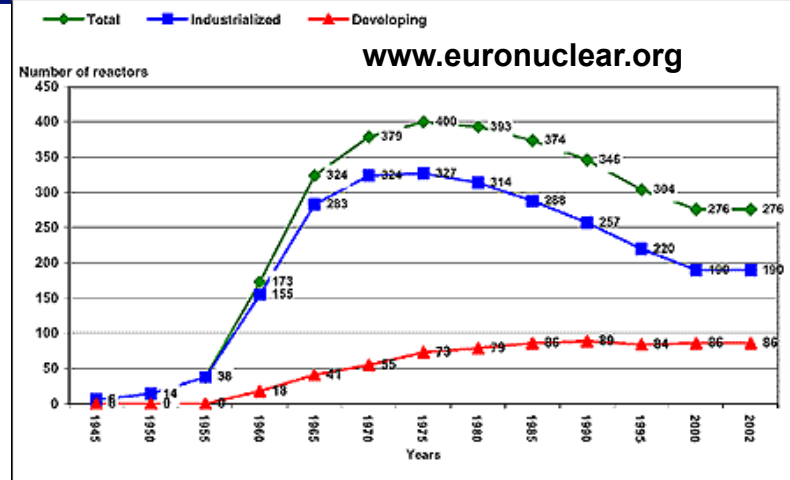
Centrifuge Diagram





Other uses of enriched uranium

Research reactors
LEU and HEU fuel
~280 operational out
of 680 built worldwide



Problem: globally dispersed
SNM, various levels of
protection

US/IAEA/European/Russian
response:
Fuel exchange and core retrofit
programs

Naval reactors
HEU fuel allows

- infrequent refueling
- rapid power draw
- compact size



Problems:

- physical protection of cores
- treaty accountability
- (one) obstacle to a ban on HEU
- core disposal



The HEU Purchase Agreement

The U.S. has agreed to purchase **500 metric tons of HEU** from dismantled Russian nuclear weapons, in the form of 15,000 metrics tons of LEU, for use as reactor fuel for U.S. commercial power reactors. So far, ~300 tons converted (not updated for 2008 activity !)



Dismantle weapon

heat metal parts in oxygen furnace to make HEU oxide

Convert oxide to uranium hexafluoride (UF_6) gas

Mix 95% $^{235}UF_6$ with 1.5% $^{235}UF_6$ in a 'Tee'
output = 5% $^{235}UF_6 \rightarrow$ LEU

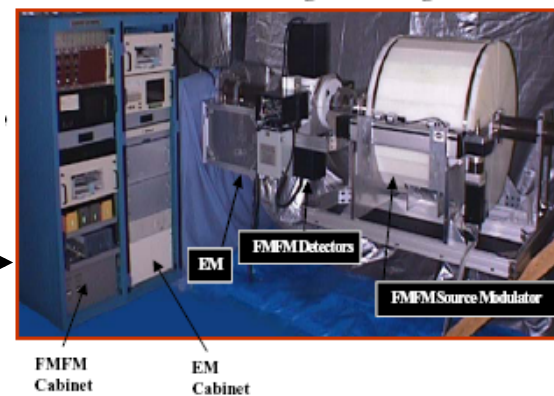
LEU fuel used in U.S. reactors



usec.com

Blend-Down Monitoring System

BDMS for one Leg of Blending Tee



Effect on fuel supply – moderately disruptive
 Operates all ~104 US reactors for over 2 years
 Effect on HEU stocks and nonproliferation regime
 – highly beneficial



Inside a typical uranium fueled reactor core

~1 cm³

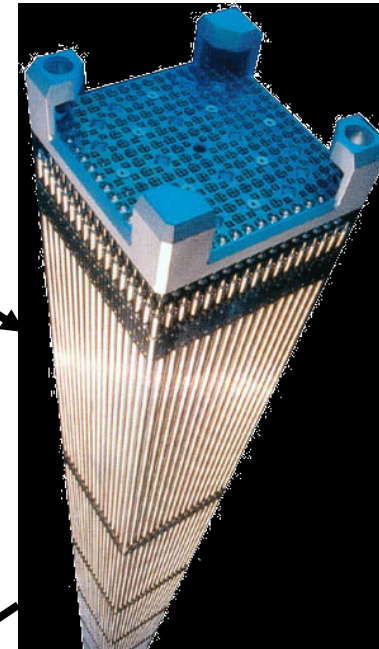


Enriched
UO₂ fuel pellets



Hundreds of pellets
In a fuel rod

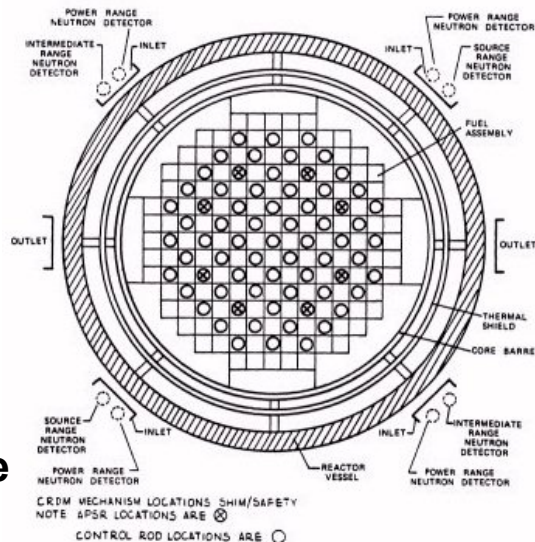
2-3 meters tall



Dozens of fuel rods
Per assembly

2-3 meters tall
~0.25 m wide

FIGURE-4 TOP VIEW OF REACTOR CORE



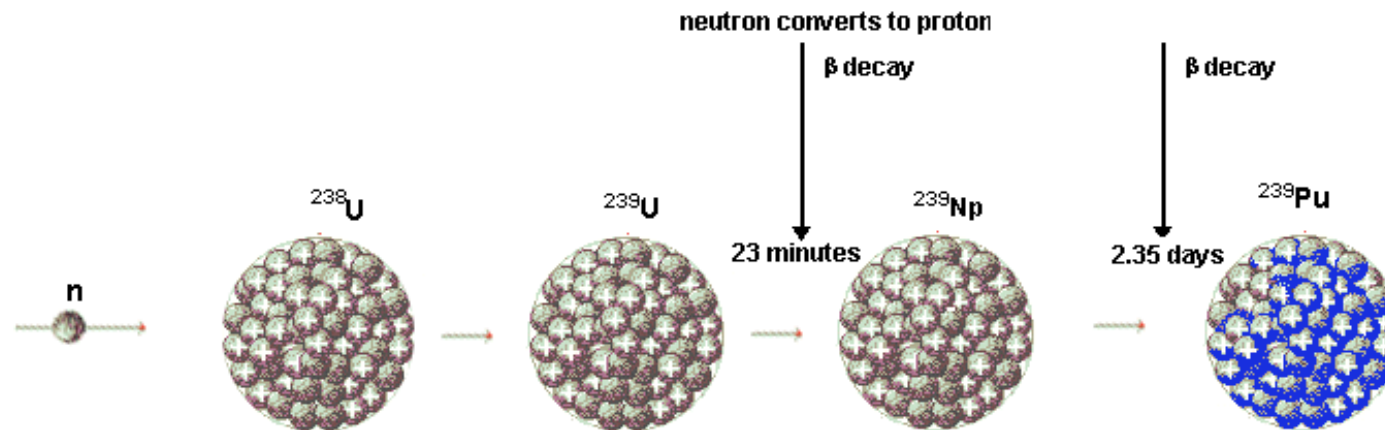
3 meters tall
2 meters wide

A few hundred fuel assemblies per core



Plutonium alchemy occurs in reactor cores

Alchemy: Plutonium is produced in nuclear reactors by bombarding “fertile” U-238 with neutrons



Every reactor in the world produces some plutonium
A typical power reactor produces about 300 kg per year

$^{232}\text{Th} \rightarrow ^{233}\text{U}$ is an alternative fissile material production mechanism
being considered by some countries



Reactors sustain their reactions in different ways or: Why enrichment is not always necessary

Slow neutrons (2200 meters/second) are much more likely to cause fission in ^{235}U than **fast neutrons**

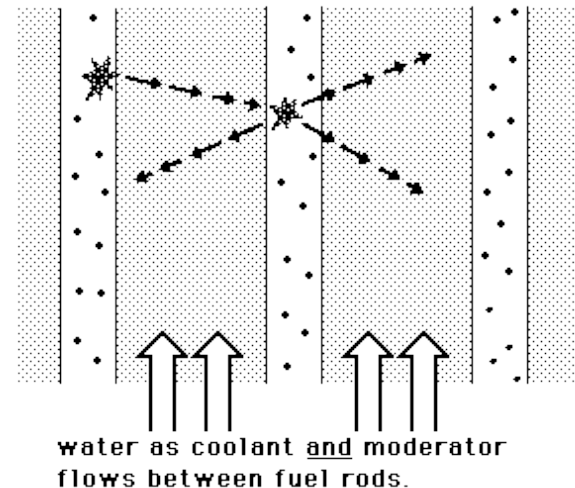
But fissile materials produce **fast neutrons**

Most reactors use water as a '**moderator**' to slow down neutrons

The water reduces the speed of fission-generated neutrons, increases the chance of fission and **ensures that criticality is maintained**

The problem with water: water also absorbs neutrons before they have a chance to cause fission

Result: natural uranium doesn't have enough ^{235}U density to sustain a chain reaction when surrounded by water →



Water moderated reactors need ^{235}U enriched fuel

Graphite and Heavy Water don't slow down neutrons, as well as Light Water, but they **absorb far fewer neutrons** →

Graphite and Heavy Water moderated reactors can use natural uranium – these moderating materials are therefore proliferation sensitive



All reactors produce some plutonium, some are best for weapons plutonium

- natural uranium fueled reactors have some advantages for weapons Pu production
 - The most efficient way to produce Pu
 - Don't need to buy or make enriched uranium
 - Reactor must use either **Heavy Water** or **Reactor grade graphite** – both are difficult to obtain
- A 40-MW natural uranium fueled reactor will produce about 8 – 10 kg/yr plutonium, enough for 1 weapon/yr
- A good rough rule of thumb:
1 gm of Pu production per MegaWatt-Day of operation



Heavy Water Plant
Rajasthan, India



Plutonium isotopes, grades of material, and weapons design

- **There are many isotopes of Plutonium, only the odd isotopes are fissile**
- **Sub-optimal even isotopes (Pu240) build up over time**
- **The economics of nuclear power encourage a long fuel residence time in a reactor (years)**
 - “Reactor-Grade” Plutonium may have only 60% ^{239}Pu
- **The physics of nuclear weapons encourages a short fuel residence time (months)**
 - “Weapons Grade” plutonium is at least 90 % ^{239}Pu (IAEA)

“Reactor-grade” plutonium is still usable in weapons and must be closely controlled

Note: This statement still generates controversy in some circles !

See e.g. J. Carson Mark, "Explosive Properties of Reactor-Grade Plutonium," Science & Global Security 4 (1993)
And

Reactor-Grade and Weapons-Grade Plutonium in Nuclear Explosives“, in "Management and Disposition of Excess Weapons Plutonium,“, National Academy of Sciences, Committee on International Security and Arms Control, W.K.H. Panofsky, Chair, January 1994, pp.32-33.



Plutonium reprocessing

- Plutonium in spent fuel is mixed with highly radioactive fission products
- spent fuel is 'self-protecting' – how self protecting depends on the degree of 'burnup' or irradiation
- in this form it is useless for weapons production
- to extract the plutonium, the fuel must be re-processed

How is it done ?

1. Slice up fuel rods
2. Dissolve in nitric acid
3. Mix acid with an oily substance that absorbs Pu and U only
4. recover oil and precipitate out Pu/U

Reprocessing plant characteristics

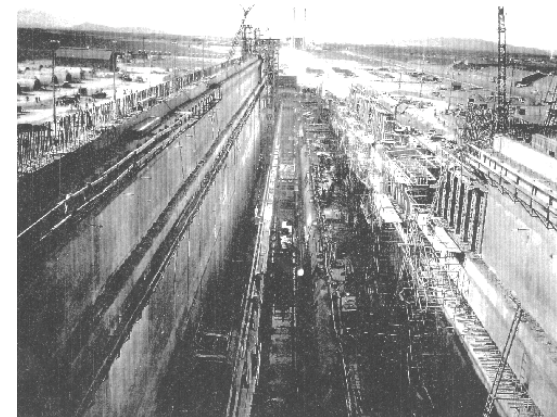
2 meter walls, remote or robotic handling, and good filtration systems for highly radiotoxic plutonium dust.

Determined proliferators could relax these requirements - up to the limit of lethality



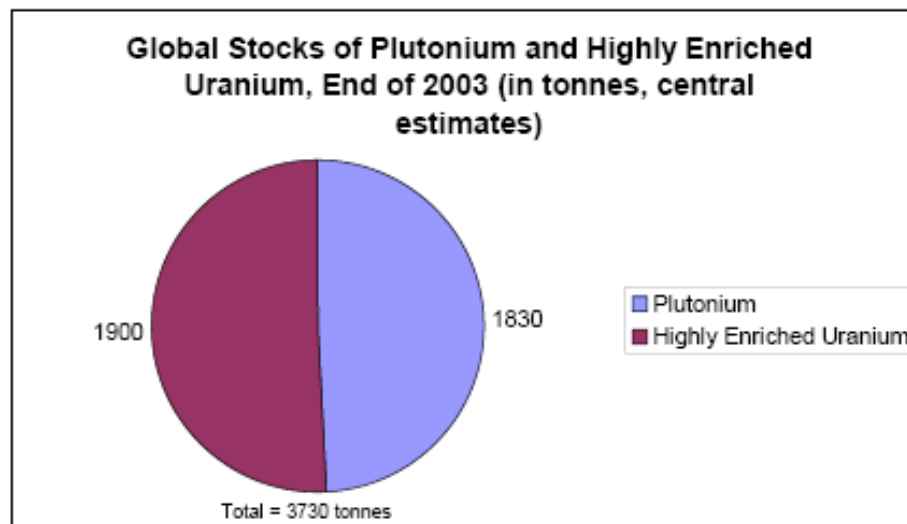
An ingot of separated plutonium

“A dangerous and dirty business”



A large U.S. Cold War reprocessing plant

How much plutonium and HEU are in the world ? (unclassified estimates)



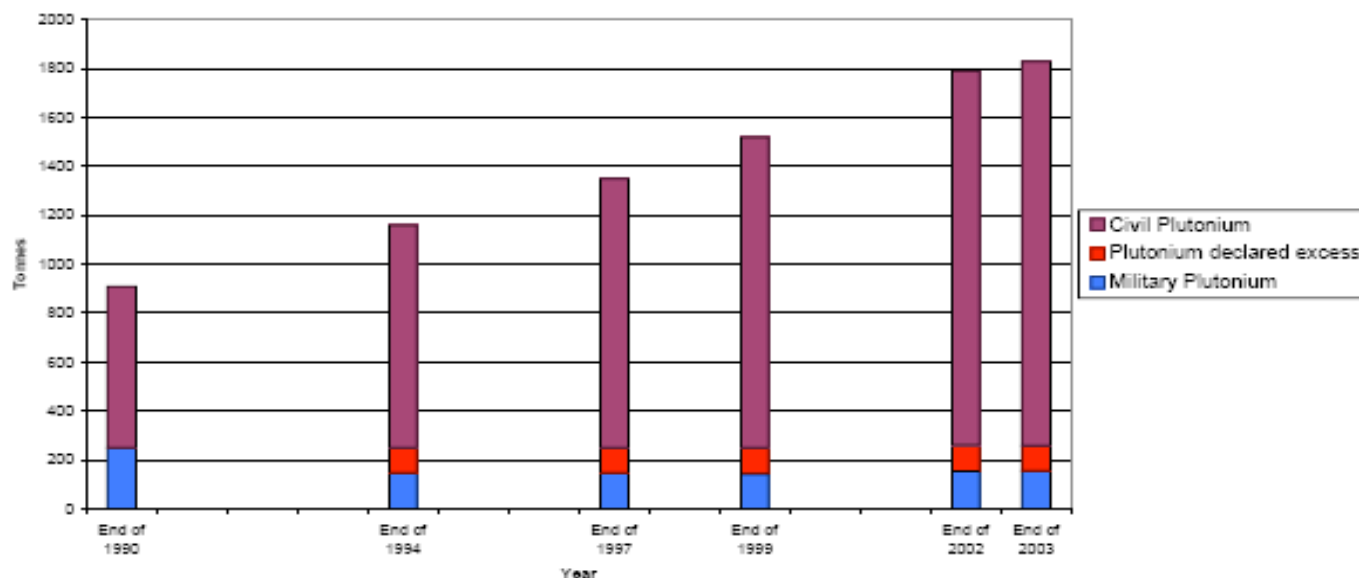
Total HEU: 1900 tons, 90% military
Total plutonium: 1830 tons

Separated plutonium:

- 340 civil (includes mil. surplus)
- 150 military
- **490 total separated plutonium**

<http://www.isis-online.org>

Global Inventory of Plutonium (all quantities in tonnes)

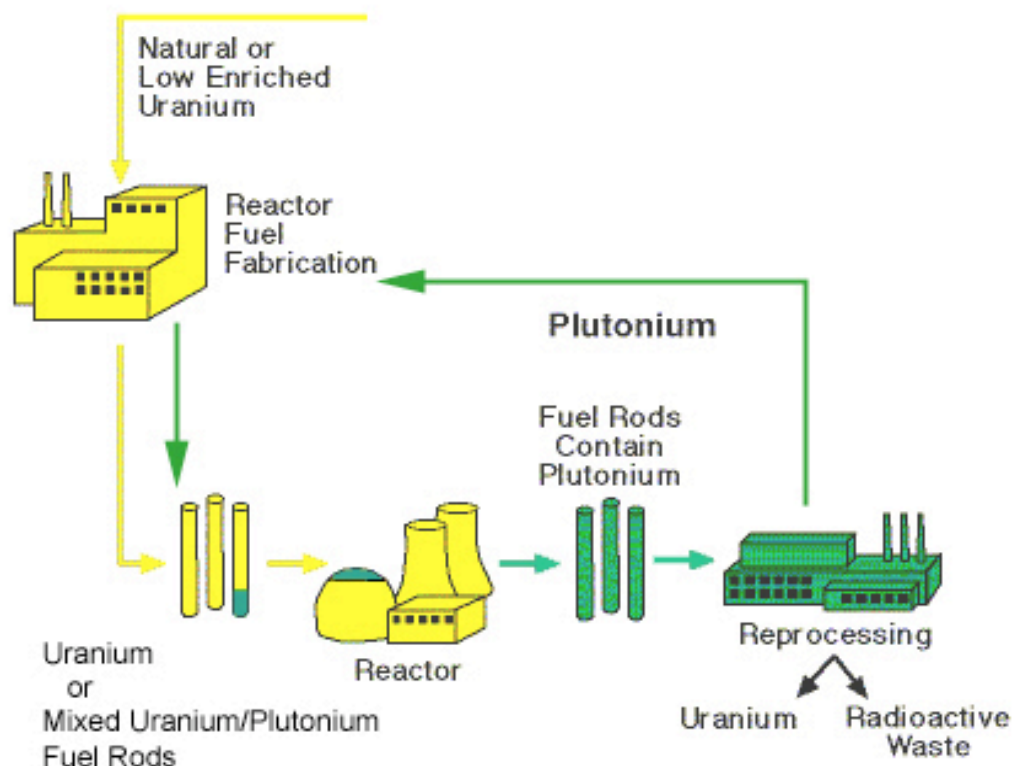




“Closed” power production fuel cycles are particularly sensitive

Closed or Reprocessing fuel cycles are those in which separated, directly weapons-usable plutonium is generated

Open Fuel cycles don't contain directly weapons-usable material – it remains locked in the highly radioactive spent fuel



Variations on these two basic fuel cycle types are now being considered worldwide...



Final observations

- Nuclear power has not spread as quickly as once predicted
- As a result the state of the art in nuclear technology has not changed much in the past few decades

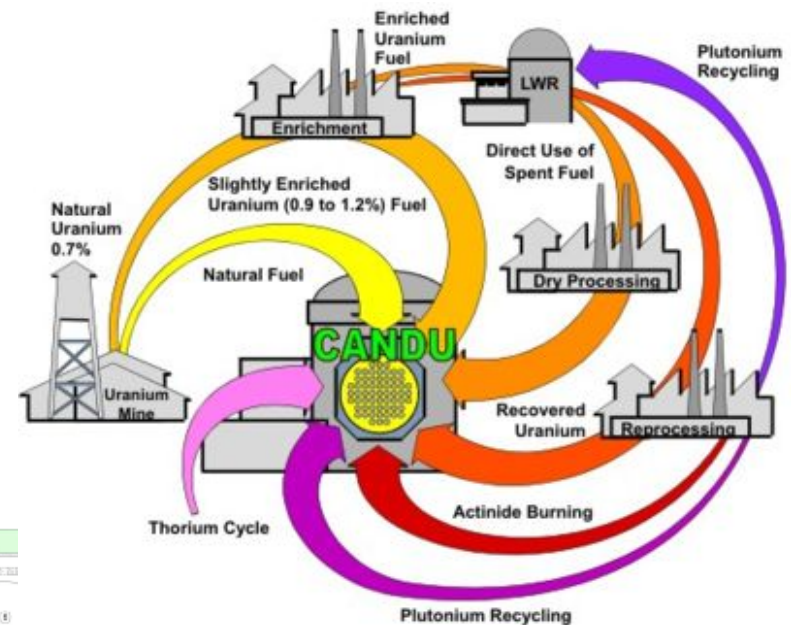
But

Global warming and oil supply concerns are spurring new nuclear cycle development

Technical barriers to proliferation are continually being lowered

New fuel cycles and proliferation problems may not be far off...

Example: Low power (300 MWe) reactors with ten-year fuel residence times



Example: CANDU with diverse fuel options



Figure 2 SMART Combined Layout (Elevation View)

The proliferation impacts of new cycles must be carefully examined